FLOW AND NOISE CONTROL: TOWARD A CLOSER LINKAGE

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Abstract

Motivated by growing demands for aircraft noise reduction and for revolutionary new aerovehicle concepts, the late twentieth century witnessed the beginning of a shift from single-discipline research, toward an increased emphasis on harnessing the potential of flow and noise control as implemented in a more fully integrated, multidisciplinary framework. At the same time, technologies for developing radically new aerovehicles, which promise quantum leap benefits in cost, safety and performance benefits with environmental friendliness, have appeared on the horizon. Transitioning new technologies to commercial applications will also require coupling further advances in traditional areas of aeronautics with intelligent exploitation of nontraditional and interdisciplinary technologies. Physics-based modeling and simulation are crucial enabling capabilities for synergistic linkage of flow and noise control. In these very fundamental ways, flow and noise control are being driven to be more closely linked during the early design phases of a vehicle concept for optimal and mutual noise and performance benefits.

1 Introduction -Demands Driving Linkage

Because of continuing demand for low-noise aircraft, advanced technologies are required to meet certification and airport community requirements for future aircraft. In addition, the current hub system for airports has led to a range of additional opportunities for advanced technologies as will be highlighted below. Adverse consequences of air travel are all too familiar to the traveler and airport communities in the form of noise pollution, congestion (lost time), environmental concerns (e.g., air pollution), safety, etc. These demands are exacerbated by the persistent growth in the air transport system, the fundamental hub-system operations philosophy, and are compounded by security concerns after the terrorist events of 11 September 2001.

Prior to 11 September 2001, the Federal Aviation Administration estimated that air traffic would increase 43 percent by 2011 for domestic large air carrier enplanements [1]. Major aircraft manufacturers also forecasted strong growth in traffic over the next 20 years, at about a 5-percent per annum increase. The result will be that the world's airports will have to accommodate a more than doubling of throughput. Boeing [2] projected a more than doubling of the world's commercial aircraft fleet to 32,955 by 2020. Although the terrorist events have altered this projection, the world population continues to increase and, with assured security for airports in the future, the volume of air travel will continue to grow and further increase the demands on the current air travel model.

Inadequacies of the large hub system have resulted in an increasing demand for more point-to-point travel. The demand for secure

and reliable service will only increase as congestion threatens to impact safety and timeliness. Of course, demand for low fares will continue. At some point fuel prices will become a sufficiently high portion of the total operating cost of an airline that demand for increased aircraft performance will become an important goal for the acceptance of new aircraft concepts.

Capacity, safety, and economy represent areas where the applications of innovative aerodynamic flow and noise control technology are critical to providing solutions for the needs of the future air transport system. The aerospace vehicles and transport system that one might envision for the 2020 timeframe will have stringent economic and public acceptance requirements placed on them. In some ways there are even more aggressive goals that might also be placed on the aerospace industry such as an emission-less vehicle (no air or noise pollution). Without new solutions from technology, the new transport system or aggressive goals for air vehicles that can benefit the public in such significant ways simply will not be realized.

This paper will highlight flow and noise control technologies that contribute directly and indirectly to reduce noise and emissions, to improve performance, safety, and airport operations. A more thorough discussion of these technologies is provided in a review by Thomas, Choudhari, and Joslin [3].

2 Application Linkage: Flow and Noise Control

2.1 Noise Control Revolution Required

Reducing noise emission has been an increasingly important aspect of aircraft design during the past few decades and will continue to remain so because of new certification requirements. Following the mandated phaseout of Stage II airplanes in 2000, only Stage III compliant fleets remain operational in the civil aviation fleet. The Stage III fleets are approximately 20 dB quieter than the first turbojet powered airliners. Much of this

reduction was obtained in the earlier years as engines moved from turbojet to turbofan cycles. The subsequent pace of noise reduction has been noticeably slower in comparison. Yet, the negative impact of noise on airport communities continues to drive public demand for an even quieter air transportation system.

Accordingly, new Stage IV standards have already been passed by the International Civil Aviation Organization (ICAO). The additional noise reduction to be mandated under Stage IV is 10 dB on a cumulative basis (including all three certification points) [4]. These standards would apply to new aircraft after January 2006. In addition to the ICAO standards are additional noise restrictions imposed by individual airports.

Anticipating this trend to continue well into the twenty-first century, NASA has set an aggressive goal of performing research and demonstrating technologies for reducing aircraft noise levels an additional 20 dB over the next 25 years. Such dramatic reductions are necessary to meet the anticipated demand by the traveling public and communities surrounding airports for noise reduction.

Prior experience has shown that for any newly identified noise source it is relatively easy to achieve the first few decibels of reduction in acoustic intensity by conventional design alternatives. To achieve subsequent reductions in noise levels, however, innovation is required and therefore a significantly larger effort in terms of both research and cost of implementation and an increasingly interdisciplinary effort become necessary. This is made clear, for example, with the success of a prior noise-reduction program (the noise reduction element of the NASA Advanced Subsonic Transport program) which achieved its minimum success goal of 8 dB noise reduction over 1992 technology, bringing us to this regime of increasing degree of difficulty.

For potential revolutionary reductions in noise, one must resort to unconventional design considerations such as active flow control. Flow control technology will have to be increasingly applied to noise control in order to make further noise reduction possible. A promising concept

for directly altering the mean fan wake characteristics uses trailing edge blowing, representing one example of a direct connection between flow control and noise control. This approach has been shown to reduce the tonal noise via rotor-wake stator interaction by up to 4 dB [5]. A small amount of air is channeled to the trailing edge through narrow passages in the fan blade. The passages in the hollow fan blade distribute air over the length of the trailing edge for injection. Injected air reduces the strength of the rotor wake by filling in the wake, thus greatly reducing unsteady pressure fluctuations on the stator downstream. Even with presumably little performance penalty, trailing edge blowing must still be developed further and contend with similar issues as laminar flow control (i.e., need for plumbing, maintenance issues, etc.) before it can be applied on actual turbofans.

Also being investigated are numerous other examples of noise control strategies that are directly related to flow control technologies such as jet noise reduction by nozzle trailing edge modifications.

2.2 Flow Control's Enabling Technologies

A number of flow control technologies have the potential to enable radically different new aircraft configurations. These technologies, if fully developed and implemented from initial design would change the paradigm for noise signature of aircraft in addition to the performance and economics of air transport systems. To illustrate the coupling benefits of noise and flow control, laminar flow control and separation control will be discussed in light of the total impact of the technology including the complete noise impact. Additional technologies are discussed in Thomas, Choudhari, and Joslin [3].

2.2.1 Laminar Flow Control

Laminar flow control techniques have been under development and testing since the late 1930's [6]. The utility of this technology is for cruise flight only, covering 80 percent or more of an aircraft's operation envelop. This benefit is achieved via small levels of suction through a porous wing/nacelle skin. This technology is included here because it is one of the few technologies that have matured via technology readiness level (TRL) improvements through flight demonstrations on transport size aircraft.

Natural laminar flow (NLF) employs a favorable pressure gradient to delay the transition process. This delay in transition yields either faster aircraft speeds or reduced fuel consumption and emissions. Such a technology is desirable because no additional hardware is required to achieve the benefits of NLF. Although many difficulties with proposed NLF concepts have been overcome, insect and debris contamination on a surface (usually near the leading edge of the article) can cause portions of the NLF article to become turbulent and therefore degrade the system benefits. Numerous successful flight experiments [6] have used paper covers, scrapers, deflectors, fluidic covers, thermal covers, liquid discharge, and flexible covers to prevent and/or overcome issues relating to insect/debris-induced roughness. For some obvious reasons, these techniques, although successful for flight test vehicles, become impractical for production vehicles. Hence the operational environments could make this concept impractical; however, small aircraft could employ the NLF concept simply by cleaning the wing leading-edge regions prior to each flight. During the flight some small loss of performance can result due to insect encounters, but this is only a regional and seasonal impact on performance for some aircraft.

Laminar flow control (LFC) is an active boundary layer flow control technique employed to maintain the laminar flow at chord Reynolds numbers beyond that which is normally characterized as transitional or turbulent in the absence of control. Hybrid laminar flow control (HLFC) integrates the concepts of NLF with LFC to reduce active system requirements and reduce system complexity. These concepts, when integrated with the Krueger flap (for high-lift and ice and

insect-contamination prevention), showed one potential practical application of HLFC on a wing [7].

Benefits of the variations of LFC are configuration dependent, change with time due to changes in fuel cost, system cost, and manufacturing technology efficiency improvements, and are closely linked to the amount of laminar flow and a host of other variables. Probably the single largest driver is the cost of fuel; however, LFC can also be used to introduce a new variable in the design trade offs that affects weight, noise, range, and other parameters [8]. Due to uncertainty in the extent of laminar flow achievable and penalties of the technology, benefits can range from reductions of 6 to 13 percent in total vehicle weight, 15 to 20 percent in block fuel, or a 15- to 25-percent increase in cruise distance. Quantitative estimates of noise reduction or emission/pollution reductions have not been published to our knowledge and clearly depend on the trade-off analysis in the LFC aircraft design. For example, retaining the same specifications of a turbulent designed aircraft would yield more range and no noise reduction except in possible cabin noise reductions due to a laminar boundary layer. However, a constant range scenario would have a smaller aircraft due to lower fuel requirements and therefore smaller engines would be required; hence, airframe and engine noise levels decrease for a LFC aircraft.

Obstacles for LFC include losses of laminar flow regions due to contamination (insect), the uncertainty in the design tools, and manufacturing costs of a LFC wing/nacelle. In spite of these obstacles, the overwhelming success of the multiyear operation of the Jetstar flight experiment [9] demonstrated operational testing of LFC in an operational air service environment.

Over many years of research, this example technology was demonstrated via numerous wind tunnel and flight tests solely for benefits to aircraft performance. Clearly, these performance benefits indirectly contribute to potential noise and fuel emission reductions and lower takeoff/landing noise pollution via

smaller aircraft. So this technology may be beneficial to future aircraft both to reduce fuel costs and to meet noise certification goals.

2.2.2 Separation Control

Various passive and active flow control systems have been proposed and selectively demonstrated to replace conventional high-lift systems.

Lin [10] has shown that using micro-vortex generators (VGs) on the flap of a high lift system can mitigate flow separation, leading to a 10-percent increase in lift and a 50-percent reduction in drag. Together this leads to over a 100-percent increase in L/D. For the conventional high-lift system, the micro-VGs are used to correct inefficiently or inadequately performing systems.

Circulation control on a wing has also been investigated to generate increased lift coefficients including on full-scale aircraft [11]. Engine bleed air is blown through a slot on the upper wing surface just upstream of the rounded trailing edge. This blowing increased lift by several times compared to a conventional passive flap system. The application of circulation control technology to both lifting and control surfaces has the potential to provide improvements in performance and operational capabilities of both commercial and military aircraft. There is no complete assessment of the impact on noise emissions or manufacturing and operational costs.

An alternate to steady blowing for circulation control is the use of unsteady blowing in an attempt to reduce the amount of energy requirements to the control system. As such, separation control by unsteady tangential blowing over the flap of a wing/flap model was compared with steady blowing control by Oyler and Palmer [12]. The experiments suggested that a significant reduction in the amount of mass flow could be realized through unsteady blowing. As the pulsed frequency increased up to 60 Hz, lift also increased. Beyond 60 Hz, little or no gain in performance was measured.

Magill and McManus [13] experimented on a variety of configurations demonstrated that the use of pulsed vortex generator jet (PVGJ) effectors near the leading edge of wings can mitigate the otherwise separated flow at high angle of attack. The approach has been demonstrated with frequencies ranging from approximately 10 to 250 Hz and is also a function of the directivity of the jets and jet/free-stream velocity ratio. Open loop results have been used to develop control laws [13] for PVGJs, and closed loop control was demonstrated in the experiments. This technology is important for high-angle of attack situations near wing stall. Clearly, the range of frequencies for this control technology must be considered to avoid excitation of noise generation mechanisms.

Separation control on a two-dimensional airfoil at angle of attack has been demonstrated in low and high Reynolds number wind tunnel experiments by the introduction of periodic momentum mass flux through a slot opening in the model [14]. Although an oscillatory blowing valve was used to generate the periodic disturbance, any type of actuator having similar performance characteristics could have been used.

An oscillatory blowing valve was chosen because of the ease with which a steady disturbance, oscillatory disturbance, or superposition of steady and oscillatory disturbance could be generated. This technique was effective because it promoted mixing between the higher momentum fluid above the otherwise separated region and the lower momentum fluid at the surface. The enhanced mixing brings the higher momentum fluid close to the surface, making the boundary layer more resistant to separation. This active means of control has the advantage of eliminating or reducing separation without the performance degradation at off-design conditions associated with passive control. Also, the periodic control is two orders of magnitude more efficient than steady suction or blowing traditionally used for separation control [14]. As with the PVGJ technology, the range of frequencies for this control technology must be considered to avoid excitation of noise generation mechanisms.

Whereas the conventional high-lift system is a multi-element airfoil for transport aircraft, the zero-net-mass oscillatory excitation high Reynolds number experimental results suggest that an alternate simple flap/slat with flow control could replace the multi-element system. As such, the first systems analysis was undertaken to estimate the benefits of replacing the conventional high-lift system with a flow control high-lift system [15]. Assuming no performance gain with a flow control system, and by extrapolating the two-dimensional wind tunnel experimental results to scale, the study suggested that benefits such as part count reductions and weight reduction were possible with the flow control high-lift system.

Hence, similar to the LFC technology, the total aircraft weight reduction can ultimately reduce the airframe and engine noise and possibly air transport capacity issues. Unlike LFC, the oscillatory control technology is in an *embryonic* stage and will ultimately require many more years of wind tunnel testing, prototype flight testing, and a full scale demonstration to raise the TRL and to quantify the full performance and noise benefits of this technology.

3 Physical Linkages: Flow and Noise Control

3.1 Broadband Control

Given the need for continued noise reduction extremely innovative approaches will be required to achieve projected targets during the next two decades. As the dominant tones are successfully reduced using technologies developed during the Advanced Subsonic Transport program, further reductions in the overall noise spectra will be controlled by the various sources of broadband noise. A complete elimination of fan tones, for example, will yield an overall EPNdB (effective perceived noise) reduction of only 2 dB, whereas additional reduction will have to be obtained via broadband noise control [16].

Because of the origin of broadband noise in flow turbulence, advances in flow and noise control technologies will have to be increasingly synergistic. The objective is to exploit the inherent synergies between the two so as to enable the development of radically new technology. Such synergies could exist either at the modeling level (i.e., physical similarities between synthetic jet actuators and duct acoustic liners would permit parallel model formulations and overlapping design tools) or extend to the implementation level (i.e., microblowing can serve the dual purpose of reduced nacelle drag and acoustic impedance control).

Fan broadband noise sources, for example, include fan self-noise as well as interaction of blades and vanes with inflow turbulence, vortex ingestion, inlet boundary layer, and wake turbulence [17]. As a result of the progress made in predicting and controlling tonal content of turbomachinery noise, broadband noise has become an additional current focus of research and represents the primary barrier to understanding the main physics of turbomachinery noise generation. Also contributing to the increased significance of broadband noise are the downward shift in tonal frequencies (i.e., away from the range of peak auditory sensitivity) and a shift higher in the broadband spectrum, resulting from the trend toward larger diameter engines, smaller number of blades with wider chord, and lower tip speeds [17].

Recent work at Boeing [17] and elsewhere (e.g., Glegg and Devenport [18]) has just begun producing the kind of insights necessary to develop a satisfactory understanding of the broadband noise phenomena. There is a strong need to continue detailed measurements of the turbomachinery flow field and also to initiate accompanying numerical simulations. These steps will be necessary in order to pin down the precise nature and hierarchy of the various sources involved so that more effective noise reduction measures can be first identified and tested, then eventually optimized. There is also a significant opportunity to exploit the physical similarities

between broadband fan noise and airframe noise in this respect. An example is the recent innovative application of the Brooks et al. [19] data (which was originally obtained in the context of rotor/airframe noise) toward the prediction of broadband fan noise [20]. The same example also underscores the importance of conducting detailed experiments on building block configurations.

3.2 Modeling and CFD

CFD will play an increasingly valuable role in the development of both passive and active flow and noise control systems by generating the necessary insights to optimize costly experimental testing. For active systems in particular, computational methods will help establish required specifications (in terms of frequency response and amplitude range) for actuators and sensors, design effective actuation concepts that require minimum energy expenditure to achieve a desired control action, and choose the best locations for these. Numerical simulations would also serve as a useful test bed toward off-line assessment of the various control algorithms.

The investigation and development of new methods for flow control will require a thorough understanding of the physics inherent in various flow control devices or concepts such as porosity, micro vortex generators, synthetic jets, and even flapping flight. Most of these concepts involve unsteady flow, and many further require a control system to achieve useful benefits in a practical application. Thus, basic behavior of a synthetic jet, for example, can be investigated with a time-accurate CFD code, but computational demonstration of active flow control will require the CFD to be coupled with numerical sensors and a control system with feedback. This has been done for simple problems [21] but is not yet usable for realistic flow control investigations. The design of certain types of devices such as those using flexible membranes—flapping flight with flexible wings, for example—will further

require coupling with structural analysis of appropriate materials.

Another future application of concurrent experimental/computational research methods to problems in flow control would involve simultaneous testing of candidate control algorithms for active flow control devices on computational and wind tunnel models. The physical understanding gained from the combined test could then be extrapolated to full scale or other configurations with much more confidence.

In noise control, high-order accurate Navier-Stokes CFD codes must be coupled with acoustic radiation codes in order to provide an analysis capability for the investigation of basic noise generation mechanisms on vehicles of interest. This capability is currently under development, and will allow various candidate approaches for noise reduction to be more fully evaluated before being incorporated into full-scale vehicles. With further refinement to include unsteady surface motion in the calculations, it would become possible to predict noise from rotating machinery problems such as ducted fans and advanced propellers (Farassat, private communication, 2000), as well as airframe noise sources such as flap side edges and landing gear.

Airframe noise work from the 1970s, especially results from flight tests of a large number of flyovers, generated a large noise databank that was used to provide an empirically based airframe noise prediction method. However, more recent theoretical and experimental work has established the basis to replace the existing prediction method with a more accurate, physics based prediction for airframe noise. While this goal appears to be significantly futuristic, recent work has focused on developing the physical understanding necessary to formulate better engineering models. In particular, work during the 1990s led to significant physical insights into the detailed fluid dynamics of relevant unsteady flow structures and how they produce noise [22]. This progress came about from a combination of new experimental and computational techniques used in parallel. Such enhanced understanding has also led to successful control concepts for airframe noise reduction on the laboratory scale.

A major focus of recent work on airframe noise has been on noise associated with the high-lift system, particularly on noise generation near a flap side edge. A combined NASA/industry team implemented an approach using a combination of detailed measurements and computations of the local flow field and the far-field acoustics. Detailed computations of the local flow include RANS computations that resolve the relevant mean flow features together with appropriately simplified simulations of large-scale fluctuations convected with mean flow features. The far-field acoustics are predicted either through a Lighthill acoustic analogy approach or by using the Ffowcs Williams-Hawkings equation. Using this type of approach, the NASA/industry team was able to correlate different parts of the far-field spectra to specific flow field features such as instability modes of the shear layer(s) associated with flow separation near the side edge, and edge vortices created by the roll-up of the shear layer [22].

Armed with a physical understanding of the noise sources involved, several passive edge treatments (such as a porous flap tip) were developed and tested. The result of the edge treatments was a reduction of 4 dB in a limited band of frequencies of noise resulting from the presence of vortices close to the side edge. The total reduction on the flap side edge would be less than this amount. A similar effort for slat noise led to the discovery that a prominent high-frequency hump in the slat noise spectrum is caused by vortex shedding from a seemingly sharp slat trailing edge [23]. The otherwise broadband noise was shown to be associated with unsteadiness of separated flow on the lower slat surface—a finding that again helped with cutting noise levels by over 5 dB in the limited frequency bands associated with the particular slat flow.

3.3 Implementation Level – Active Control

Historically, passive control techniques have dominated both flow and noise control worlds, with the control measure being implemented typically at a component level and, more often than not, on an *a posteriori* basis. This was required because typically expected performance did not materialize or because requirements or regulations changed at a later time. More recently there has been an increased emphasis on harnessing the hidden potential of active flow and noise control as implemented in a fully integrated, multidisciplinary framework.

Active techniques can be implemented in both open loop and closed loop fashion, but closed loop devices (i.e., with feedback) offer the maximum potential in terms of optimal overall performance. Control algorithms for linear, time invariant, fully deterministic systems are well established. However, high Reynolds number flow systems are inherently stochastic in nature, tend to involve a prohibitively large dimension (i.e., number of degrees of freedom), and more often than not, require a significant nonlinear coupling between the various states. Successful application of modern control concepts is, therefore, far from proven and will require significantly higher physical insights into the various flow systems that are encountered in aeronautical applications.

Efficient design of massively actuated systems, characterized by a large number of discrete or distributed actuators, will require tools to optimize the number and spatial locations of both sensors and actuators. There has been considerable research in a variety of disciplines on actuator and sensor placement, either to optimize the controllability and observability of the system or to maximize some objective function of control system performance. In addition, for adaptive control, the sensor and actuator locations must also be optimized for the accuracy of system identification.

Active control of jet noise, via unsteady actuators mounted near the nozzle exit, is an attractive option from the standpoint of maintaining an optimal aerodynamic performance under a wide range of operating conditions. Despite its demonstrated ability to increase jet mixing, active jet flow control has generally proven unsuccessful at reducing noise and has actually increased far-field noise in some cases [24]. Active control of jet noise is clearly in its infancy and would require significant advances in actuation systems, control algorithms, and measurement techniques in order to realize its powerful potential. Glow discharge devices, Helmholtz resonators, MEMS, and fluidic injection are all actuation systems that indicate promise in controlling jet flow. In addition to addressing technical issues relevant to these forms of control, there is a general need to examine the robustness of such devices in the harsh environment of high-temperature jet exhaust. Due to limited access for sensors, closed loop jet noise control poses significant challenges. Because ongoing work on optical sensors may, however, remedy the need for remote flow diagnostics, there is a need to assess the relative noise reduction potential of closed loop control (in comparison to open loop techniques) in laboratory experiments.

3.3.1 Surface Porosity

Passive porosity is one example of a technology that has been used in both flow and noise control separately but that has potential to be implemented in ways that may accomplish simultaneous objectives. Passive porosity is designed to modify the surface pressure distribution. In its simplest form it consists of a porous skin over a cavity that has a solid back wall. The cavity allows pressure communication among regions of pressure differences over the area covered by the porous surface. Typically the porous surface is a skin perforated with circular holes, although many variations of porous surfaces are possible.

Passive porous technology has been studied extensively both experimentally and computationally for many flow control applications. One representative application has been alleviation of shock/boundary layer interaction. The loading asymmetry typically found on slender axisymmetric forebodies was successfully eliminated with passive porosity

[25]. This demonstrated the extension of porosity to three-dimensional flow fields.

Using similar technology, porosity has been applied to flight vehicles. A porous patch was added to the wing of the F/A-18E to solve a problem of uncontrolled roll discovered during initial flight tests [26]. Current research is investigating the development of design tools for complete aircraft configurations. The goal is to study the potential of replacement of conventional aerodynamic control effectors with passive porosity effectors in the design of a generic tailless fighter aircraft [27]. Passive porosity effector configurations were found to be competitive with conventional control approaches.

Passive porosity technology is advancing to develop adaptive control techniques based on variation of porosity parameters via microelectromechanical systems (MEMS), smart memory alloys, or other smart skin. Alternatively, performance of the control system can also be affected by varying the plenum properties via similar means.

Simplified models for the effects of porosity have been developed and used in production CFD codes [28]. However, the development of comprehensive models describing more detailed parameters is necessary to fully exploit porosity in design of applications. Other applications that have been studied include separation control in cavity flows [29] and drag reduction for ground vehicles, water vehicles, and ground structures.

While passive porosity as described above has been developed for aerodynamic flow control for years, porous sheets are also a basic component of acoustic liners. The understanding of the interaction of sound and porous sheets and the ability to model and predict their behavior have been subjects of research in acoustic liners for decades. Lee [30] and Brooks [31] both proposed the use of porosity devices in the development of noise reduction methods for rotor blade vortex interaction noise. As discussed earlier, porosity is also a method that has been investigated in addressing flap side edge noise. Porosity represents one example of technology that crosses over between flow and noise control areas and, in the future, combining knowledge from the respective areas could probably produce greater advances in tools with which to apply porosity. It could also result in greater synergy in the application of porosity for both noise and flow control reasons simultaneously.

4 Summary

Technologies for developing radically new aerovehicles, which would combine quantum leaps in cost, safety, and performance benefits with environmental friendliness, have appeared on the horizon. Bringing their promise to reality will require an increasingly interdisciplinary approach between flow and noise control communities, coupling further advances in traditional areas of aeronautics with intelligent exploitation of nontraditional, interdisciplinary technologies such as smart, distributed controls, novel actuators, MEMS, and many others.

In both application and in very fundamental ways, flow and noise control technologies are being driven to be more closely linked. Exploiting the synergies between the two areas will be related to physical understanding and modeling of critical flow features, development of control strategies for broadband noise and turbulence, integration of passive and active control devices, efficient design of control systems, and the deployment of CFD techniques in the above areas.

As outlined briefly in this paper, future requirements will be demanding and are likely to mandate a rethinking of the best aircraft platform to best enable the overall success of the commercial transport system in meeting future demands. This represents another future direction with great potential for impacting not only the way aircraft look 20 years from now, but also their capabilities toward aggressive goals. This future direction involves the system level design of aircraft and specifically the integration of propulsion and airframe for configurations that are unconstrained by the current, prevalent configuration to best take

advantage of revolutionary flow and noise control technologies.

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